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Pilot attention allocation model based on fuzzy theory

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ABSTRACT

Quantitative research into a pilot's attention allocation mechanism is required in the optimization design of an aircraft human–machine interface and system evaluation. After making a comprehensive consideration of several factors, including the importance of information, information detective efficiency and human errors, a pilot attention allocation model was built on the basis of hybrid entropy. In order to make a verification of the pilot attention allocation model, a simulation model of a head-up display (HUD) used to present flight indicators was developed. After setting the membership degrees of the importance for different indicators according to their priorities, the experiments on the key-press response and eye-movement tracking were designed and carried out under the cruise and hold modes. As the experiment results are in good agreement with the theoretical model, the effectiveness of the pilot attention allocation model based on fuzzy theory is confirmed.

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1. Introduction

In the human–machine interaction system of modern aviation, the role of the pilot is transforming from an operator to a monitor due to the improved aircraft performance and automation [1]. The pilot needs to keep monitoring various indicators simultaneously when carrying out flight missions. Therefore, getting visual information effectively greatly depends on a reasonable allocation of the pilot's limited attention resource. It was found that the factor of attention allocation always ranks in the top 20 after ordering 114 human factors which relate to flight deck automation according to different criteria [2]. Consequently, researching the attention allocation behavior of the pilot is of significance to offer a scientific reference for the human–machine interface design of an aircraft cockpit and thus it is helpful in improving the flight performance and safety.

As the mechanism of attention allocation is manipulated by the human brain information processing system, and is affected by the physiological and psychological factors to a great extent, it is difficult to definitely interpret the human attention allocation mechanism using the biomedical method at the present stage. Therefore, there has been a substantial interest in making a quantitative solution to this problem from the perspective of engineering psychology.

Human behavior models have been used effectively in the process of analysis, design and evaluation for various human–machine interaction systems. However, because of the non-linearity, randomicity, discretization and time variation of human behavior, many difficulties exist and a great deal of attention has been paid to the in-depth study of this field in cognitive engineering [3]. In the prior studies, many valuable models have been proposed to describe and predict the attention allocation strategy in the monitoring behavior of the human–machine system. In 1964, Sender provided one of the first quantitative models of monitoring behavior by introducing the concept of bandwidth [4]. Kleinman built the attention allocation model using a gradient algorithm within the framework of the optimal control model (OCM) of human response and verified it according to the hover control task for a CH-46 helicopter [5]. Bohnen and colleagues distinguished the factor of alarm rate from bandwidth and make optimization of Sender's model [6]. Wickens and colleagues researched the effect

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of value, effort, salience, habit, expectancy and context on the pilot's scanning behavior and built the SEEV model [7–9]. In order to express the fuzziness of human behavior, fuzzy control models have been applied well to explain the uncertain phenomenon related to the human psychological state and thinking activity. Based on it, Nobuyuki Matsui and Yan Lou built fuzzy control models of human attention allocation behavior [10,11]. However, some influencing factors which may affect human attention allocation behavior have not been considered in these models; besides, the usability of the models has not been verified.

For the monitoring task of indicators in the aviation field, the acquisition of flight information is mainly based on the pilot's previous knowledge and experience. It is due to voluntary attention driven by the top-down information processing mechanism [12]. Therefore, the attention resource allocated to a certain indicator depends on its significance as evaluated by the pilot. The prior studies also indicated that the value which represents the importance of the indicator is the most important influencing factor in pilot attention allocation behavior [13]. Besides, the attention intensity for a certain indicator is also affected by the pilot's physiological and psychological states. Insufficient understanding of the indicators or unreasonable design of the information display interface usually results in human error, such as omitting, misreading or misjudgment of the information. For such a reason, even the most important indicator may be ignored and cannot activate the attention mechanism. It means that the attention mechanism has randomness and whether the importance of a certain indicator can be correctly evaluated depends on some incidence probability. Therefore, human errors as an influencing factor should also be taken into consideration when the model is built. Moreover, in the practical application, due to different visual coding (such as color, shape, size, etc.) and processing depth (such as identification, memory, calculation, etc.) of the information, the detection efficiencies of different indicators are not the same. The indicator with low detection efficiency consumes more attention resources than one with high detection efficiency, even if they are evaluated with the same importance by the pilot. Thus, we consider the detection efficiency as another influencing factor when building the pilot attention allocation model.

The present study built the pilot attention allocation model on the basis of the study by Kleinman and Nobuyuki Matsui. Using the theory of hybrid entropy, this model takes several influencing factors, including information importance, human error and detection efficiency into consideration synthetically. In order to apply the pilot attention allocation model to the aeronautic human–machine interface and making a validation of it, a HUD simulation model used to display indicators was developed. According to the different importance of every indicator under two flight modes, the membership degree of the importance for each indicator was set by a fuzzy membership function. Through measuring the behavioral performance of the participants, and combining with the real-time eye-movement data derived from the eye tracker, the actual attention allocation situation of the participants was obtained and compared with the theoretical model.

2. Pilot attention allocation model

2.1. Pilot attention allocation model based on hybrid theory

In human–machine interaction systems, if the human brain is considered as an information receptor, then a vector can be used to express n indicators which are monitored by the pilot simultaneously when they are present on the information display interface

$$Y = (y_1, y_2, \ldots, y_i, \ldots, y_n). \tag{1}$$

The information importance is usually described from two point of views, one means the information amount which is measured by bit, and the other one means the information utility which is related to the compensation for missing information. Here, the latter one is adopted. We use ω_i to represent the significance of a certain indicator y_i which was evaluated by the pilot

$$U = (\omega_1, \omega_2, \ldots, \omega_i, \ldots, \omega_n). \tag{2}$$

A fuzzy vector X is given to express the vagueness of such an evaluation, where μ_i is the membership degree of the importance for a certain evaluation ω_i

$$\mathrm{X} = (\mu_1, \mu_2, \ldots, \mu_i, \ldots, \mu_n). \tag{3}$$

The concept of fractional attention f_i was introduced by Kleinman in OCM, where f_i is the fractional number of sensory channels that carry the information when the human is considered as a multi-channel processor. It is an equivalent representation to consider the human as a time-shared, single processing channel, and then f_i is the fraction of time devoted to y_i and f_{tot} is defined as the total fractional attention or capacity devoted to the monitoring task [5]. The constraints which f_i and f_{tot} should satisfy are

$$\sum_{i=1}^{n} f_i = f_{tot} = 1, \quad f_i \geq 0. \tag{4}$$

If the pilot is regarded as an ideal monitor, then the pilot should allocate his attention resource according to the importance of each indicator, so that to make optimization of the resource utilization. Combined with the definition of fractional attention in OCM, f_i can be expressed with (5)

$$f_i = \frac{\mu_i}{\sum_{i=1}^{n} \mu_i}, \quad (i = 1, 2, \ldots, n). \tag{5}$$

However, as the existence of the randomness of the attention allocation mechanism, p_i can be assumed as the incidence probability that the pilot can correctly evaluate the importance of a certain indicator y_i

$$P = (p_1, p_2, \ldots, p_i, \ldots, p_n). \tag{6}$$

Then, combined with the subjective expected utility theory (SEU), the fractional attention which is allocated to a certain indicator y_i is modified as f_i'

$$f_i' = \frac{p_i\mu_i}{\sum_{i=1}^{n} p_i\mu_i}, \quad (i = 1, 2, \ldots, n). \tag{7}$$

Consider that the fuzziness and randomness of the human attention mechanism are two kinds of uncertainty. They can complement but cannot substitute for each other. Thus, the uncertainty results from the fuzziness and randomness together should be measured by the hybrid entropy H_{tot} [14]. As the consciousness for the importance of the indicators originates from the uncertain subjective evaluation of the pilot, in addition, with the increase of such uncertainty, the desire for obtaining information and the anxiety resulting from information insufficiency will be strengthened. Thus it is helpful to enhance the attention level. Such a phenomenon is in line with the common cognitive law. Therefore, the hybrid entropy H_{tot} can be defined as the psychological entropy of the pilot [10]. Assuming that A is a fuzzy subset of domain U, then H_{tot} is described as follows [15]

$$H_{tot}(A, P) = m(A, P) + H(P), \tag{8}$$

where $m(A, P)$ is the fuzzy entropy given by (9), and $H(P)$ is the probability entropy given by (10) [15]

$$m(A, P) = \sum_{i=1}^{n} p_i S(\mu_i) \tag{9}$$

$$H(P) = -\sum_{i=1}^{n} p_i \ln p_i. \tag{10}$$

In Eq. (9), $S(\mu_i)$ is the binary fuzzy entropy of μ_i [15], then

$$S(\mu_i) = -\mu_i \ln \mu_i - (1 - \mu_i) \ln(1 - \mu_i). \tag{11}$$

Thus, according to the Shannon additivity rule [16], the average hybrid entropy $H_{avg}(A, P)$ of n indicators can be obtained by (12)

$$H_{avg}(A, P) = \frac{1}{n} \sum_{i=1}^{n} H_{tot}(A, P) = \frac{1}{n} \sum_{i=1}^{n} (p_i S(\mu_i) - p_i \ln p_i). \tag{12}$$

The value of p_i can be estimated reasonably by introducing the maximum entropy principle [10,17]. It is easy to see that the constraints which p_i should satisfy are

$$p_i \geq 0, \sum_{i=1}^{n} p_i = 1. \tag{13}$$

According to the maximum entropy principle, the value of p_i should make the average hybrid entropy $H_{avg}(A, P)$ reach its maximum. After calculating the extreme value of the Lagrangian function L under the constraints (13), the value of p_i^* which makes $H_{avg}(A, P)$ reach its maximum is given by (15)

$$L = \frac{1}{n} \sum_{i=1}^{n} (p_i S(\mu_i) - p_i \ln p_i) - \lambda \left(\sum_{i=1}^{n} p_i - 1 \right) \tag{14}$$

$$p_i^* = \frac{\exp S(\mu_i)}{\sum_{i=1}^{n} \exp S(\mu_i)}, \quad (i = 1, 2, \ldots, n). \tag{15}$$

Substituting p_i^* into (12), then the maximum average hybrid entropy $H_{avg}^*(A, P)$ is expressed as (16). In such a case, the pilot has the highest attention level

$$H_{avg}^*(A, P) = \frac{1}{n} \ln \sum_{i=1}^{n} \exp S(\mu_i). \tag{16}$$

The detection efficiency ψ_i of a certain indicator y_i can be defined by the reciprocal of its mean response time t_i, as shown in (17). Detection efficiency ψ_i decreases with the increase of mean response time t_i. Taking the influencing factor of the

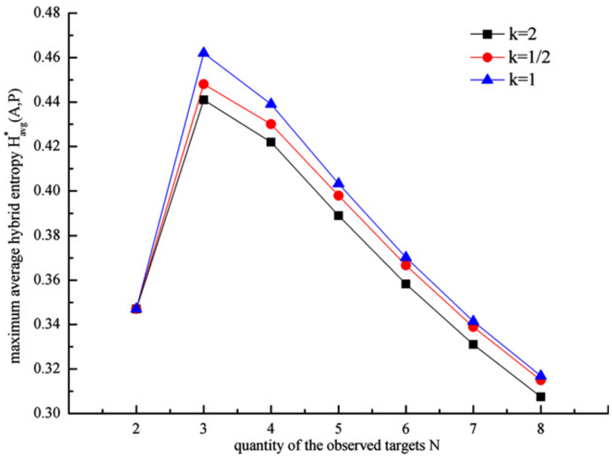

Fig. 1. Indicator quantities and their maximum average hybrid entropies.

detection efficiency into consideration, the fractional attention is rewritten as F_i, as shown in (18)

$$t_i = \frac{1}{\psi_i}, \quad (i = 1, 2, \ldots, n) \tag{17}$$

$$F_i = \frac{p_i^* \mu_i t_i}{\sum_{i=1}^{n} p_i^* \mu_i t_i}, \quad (i = 1, 2, \ldots, n). \tag{18}$$

2.2. Optimal number of indicators for attention allocation

In order to determine the optimal number of the indicators for the pilot to make an attention allocation, it is necessary to research the relationship between the indicator's quantity n and their maximum average hybrid entropy $H^*_{avg}(A, P)$. Using the calculation method of Nobuyuki Matsui and aiming at Eq. (18) built above, the membership function is supposed to satisfy the following conditions

$$\begin{cases} \mu_i < \mu_{i+1}, & (i = 1, 2, \ldots, n) \\ \mu_1 = 0, & \mu_n = 1. \end{cases} \tag{19}$$

A simple form of the membership function which satisfies the conditions above can be expressed by (20). Aiming at a different change rate k, three typical cases are selected, including $k = 1\,(\Delta^2\mu/\Delta i^2 = 0)$, $k = \frac{1}{2}\,(\Delta^2\mu/\Delta i^2 < 0)$ and $k = 2$ $(\Delta^2\mu/\Delta i^2 > 0)$

$$\mu_i = \left[\frac{i-1}{n-1}\right]^k, \quad (i = 1, 2, \ldots, n). \tag{20}$$

After calculating, the relationship of the indicator's quantity n and their maximum average hybrid entropy$H^*_{avg}(A, P)$ is shown in Fig. 1. It can be seen that $H^*_{avg}(A, P)$ present the same trend although the change rates are different. When the quantity of the indicators are 3 or 4, $H^*_{avg}(A, P)$ exhibit the higher values. $H^*_{avg}(A, P)$ decreases monotonically with the increase of the quantity of the indicators after then. Therefore, the optimal number of indicators to which the pilot can make the attention allocation effectively is 3 or 4.

3. Method

3.1. Experiment interface design

The experiment interface was designed with reference to the typical layout of an HUD. According to the optimal number of indicators for the pilot's attention allocation, four indicators of the pilot's normal work were selected, including indicated airspeed, barometric altitude, pitching angle and heading. The color of all four indicators was commonly green in the HUD. The indicators were presented on a 19-inch liquid crystal display and the resolution was 1280 × 1024.

Disturbances which made the indicator display unusual were set for each indicator by programming. The disturbance of each indicator randomly appeared with equal probability and disappeared after presenting transitorily. According to the military standard MIL-STD-1787B that the reaction time of the unusual attitude recovery should be less than 1 s, we set the duration of the disturbance to 0.8 s, and the average inter-stimulus interval between disturbances was 1 s. Each indicator

Table 1
Membership degrees of the importance and scores under the cruise mode.

Indicator	Indicated airspeed	Barometric altitude	Pitching angle	Heading
Score	9	8	5	1
Membership degree	0.9	0.8	0.5	0.1

had 20 disturbances during each experiment, and no more than one disturbance appeared simultaneously. Participants used the standard keyboard and mouse in the process of human–machine interaction.

The situation of human attention allocation can be mirrored by the eye-movement to a great extent. In order to record the eye-movement data of the participants objectively, the Smart Eye system, which is a non-contact eye tracker, was introduced in the experiment. It can track the eye movements in the completely natural state with two infrared cameras.

3.2. Experiment task

The task of key-press response was performed in the experiment. When the experiment began, the participants needed to monitor the four indicators simultaneously, and allocated their attention resource according to different flight modes. When the disturbance was detected, the participants were asked to make a response to eliminate the disturbance by pressing the corresponding key within the given time. No response, a mistaken response or a delayed response to the disturbance were all considered as noneffective attention, and the probable attention resource input was neglected. The accuracy rates and reaction times of the participants were recorded as the evaluation indexes of the behavioral performance.

3.3. Participants

Twelve students from the Beijing University of Aeronautics and Astronautics participated in the study. All the participants (8 males, 4 females; ranging from 22 to 28 years old, mean age 24.8 years) are familiar with the basic operation of a computer and have the background knowledge of aeronautics. All participants are right-handed with normal or corrected to normal vision.

3.4. Procedure

The membership degrees of the importance for the four indicators under the cruise mode and hold mode were set based on their relative priorities [18]. In order to simulate the pilot's potential experience of the importance of each indicator in a real flight environment, the membership degrees were transformed into scores by a certain ratio so that the importance of each indicator was easier to be understood by the participants. For a certain indicator, the correct response to its disturbance at each time would make the participant achieve the corresponding score. The membership degrees of the importance and the scores for each indicator under two flight modes are shown in Tables 1 and 2.

Each participant took part in the experiments under both the cruise and hold modes. The order of modes was counterbalanced across the participants. Participants practiced enough times before the formal experiment to get familiar with the process of the experiment and memorize the scores of indicators. During the experiment, the participants were required to allocate their attention reasonably according to the importance of the indicators, and try to achieve the highest total score. At the same time, the Smart Eye system kept real-time tracing.

4. Results

4.1. Theoretical results of the mathematical model

Assuming that the importance of the four indicators was the same, the mean response time t_i of each indicator can thus be measured respectively. Then the theoretical values of the incidence probability p_i and the fractional attention F_i (%) calculated by the pilot attention allocation model are shown in Tables 3 and 4.

4.2. Experimental results of the key-press response

In the experiment on key-press response, the experimental value of the fractional attention F_i' for a certain indicator y_i in one experiment can be defined as (21), where κ_i is the correct response times of y_i, t_i is the mean response time of y_i, and n is the quantity of indicators

$$F_i' = \frac{\kappa_i t_i}{\sum_{i=1}^{n} \kappa_i t_i}, \quad (i = 1, 2, \ldots, n). \tag{21}$$

According to the recorded experiment data and combined with (21), the experimental values of the fractional attention F_i' under the cruise and hold modes were obtained after statistical analysis, as shown in Table 5.

Table 2
Membership degrees of the importance and scores under the hold mode.

Indicator	Indicated airspeed	Barometric altitude	Pitching angle	Heading
Score	6	7	9	3
Membership degree	0.6	0.7	0.9	0.3

Table 3
Theoretical values under the cruise mode.

Indicator	Indicated airspeed	Barometric altitude	Pitching angle	Heading
Detective efficiency	2.04	2.08	2.33	2.02
Incidence probability	0.22	0.26	0.31	0.21
Fractional attention	35.01	36.40	24.65	3.94

Table 4
Theoretical values under the hold mode.

Indicator	Indicated airspeed	Barometric altitude	Pitching angle	Heading
Detective efficiency	2.04	2.08	2.33	2.02
Incidence probability	0.28	0.26	0.20	0.26
Fractional attention	28.72	30.92	26.70	13.66

Table 5
Mean percentages (with standard deviations) of the fractional attention F_i' under the cruise and hold modes.

Flight mode	Fractional attention F_i'/ %			
	Indicated airspeed	Barometric altitude	Pitching angle	Heading
Cruise	37.62 ± 3.09	35.85 ± 3.18	20.95 ± 2.71	5.57 ± 1.37
Hold	29.24 ± 3.52	33.26 ± 2.40	26.25 ± 3.86	11.25 ± 2.55

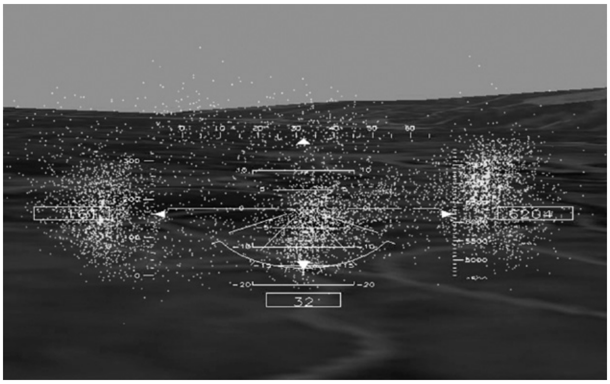

Fig. 2. Fixation points under the cruise mode.

4.3. Experimental results of the eye-movement tracking

In the experiment on eye-movement tracking, the infrared images were transformed into digital images by a PCI frame grabber with the sampling rate of 60 Hz. Therefore, in one experiment, the ratio of the fixation points m_i for a certain indicator y_i to the fixation points for all four indicators can be defined as the experiment value of the fractional attention F_i''. n is still the quantity of indicators

$$F_i'' = \frac{m_i}{\sum_{i=1}^{n} m_i}, \quad (i = 1, 2, \ldots, n). \tag{22}$$

As shown in Fig. 2, a certain participant's fixation points were recorded by the Smart Eye system under the cruise mode in one experiment. The distribution of the fixation points for each indicator can be seen intuitively. In Fig. 2, the indicated airspeed, barometric altitude, pitching angle and heading have 33.03%, 33.49%, 30.89% and 2.60% fixation points, respectively. Fig. 3 presents the fixation points under the hold mode in one experiment, where the indicated airspeed, barometric altitude, pitching angle and heading are 26.95%, 31.15%, 26.63% and 15.26% fixation points, respectively.

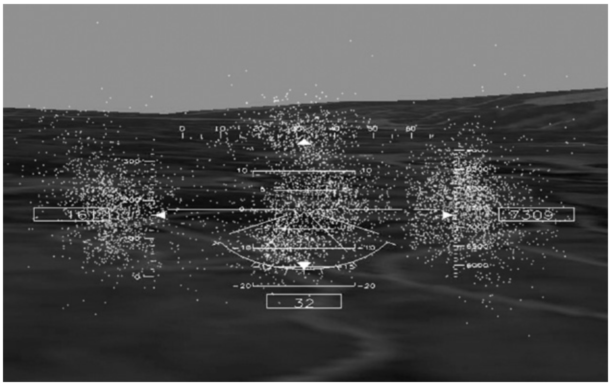

Fig. 3. Fixation points under the hold mode.

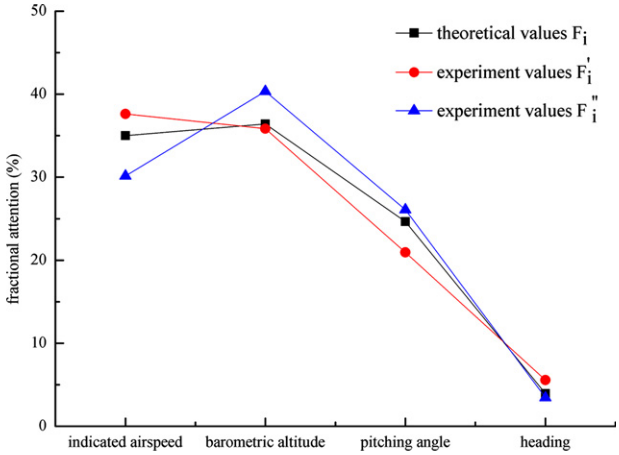

Fig. 4. Comparison of the theoretical and experimental values under the cruise mode.

Table 6
Mean percentages (with standard deviations) of the fractional attention F_i'' under the cruise and hold modes.

Flight mode	Fractional attention F_i' / %			
	Indicated airspeed	Barometric altitude	Pitching angle	Heading
Cruise	30.14 ± 4.33	40.33 ± 3.01	26.08 ± 5.49	3.46 ± 1.82
Hold	27.75 ± 3.24	35.88 ± 3.84	21.59 ± 4.59	14.78 ± 3.12

Statistically analyzing the recorded fixation points, the experiment values of the fractional attention F_i'' under the cruise and hold modes are shown in Table 6.

4.4. Comparison of the theoretical and experimental results

Under the cruise and hold modes, the fractional attention values of the key-press response experiment F_i' and the eye-movement tracking experiment F_i'' as well as the theoretical value F_i are compared, as shown in Figs. 4 and 5.

5. Discussion

It can be seen from Figs. 4–5 that the data gathered from experiments are consistent with the theoretical values calculated from the pilot attention allocation model. Thus the effectiveness of the model is confirmed. According to the pilot attention allocation model, the indicator with the highest priority may not obtain the highest attention resource due to the existence of human error and detection efficiency. This conclusion has also been embodied in the experiments. For example, the priority of pitching angle was the highest under the hold mode. However, the actual attention resource allocated to it was less than the ones allocated to the indicated airspeed and barometric altitude in the key-press response and eye-movement tracking experiments, as shown in Fig. 5.

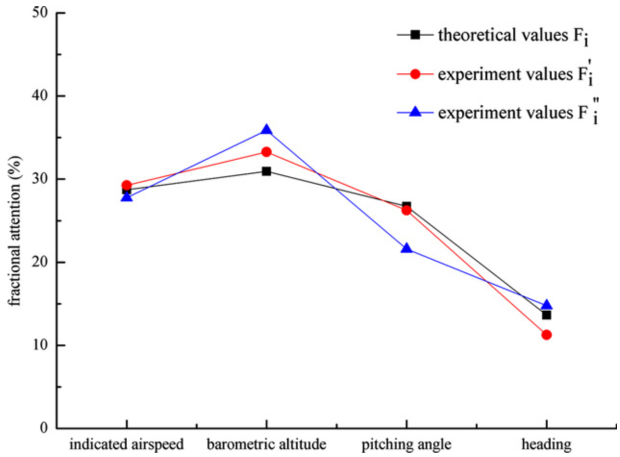

Fig. 5. Comparison of the theoretical and experimental values under the hold mode.

In our study, two different experimental methods have been adopted for analyzing the actual situation of the participants' attention allocation. According to Figs. 4 and 5, it can be seen that the results of the key-press response experiment were in better agreement with the theoretical values. This may be because the fixation points recorded by the eye tracker cannot always mirror a participant's actual observation positions. For instance, without moving the positions of the eyes, the participant can monitor other indicators by split vision. Comparatively, the action of the key-press proves effectively that the participant has allocated his attention to the relevant indicator.

According to the pilot attention allocation model, the optimal number of indicators to which a pilot can assign attention allocation effectively is 3 or 4. At this time, the pilot has the highest attention level and can allocate his attention resource reasonably according to the information priority.

Although the pilot's attention allocation behavior is mainly driven by the top-down mode, several bottom-up factors which influence the involuntary attention also exist. However, related research showed that the bottom-up factors hardly disturb the scanning strategies for the well-trained pilot [9]. Therefore, the effects of bottom-up factors on the pilot's attention allocation behavior were ignored when the model was built.

In addition, the factor of indicator location which relates to the scanning habit should also affect the pilot's attention allocation behavior. At present, this study has not taken this factor into consideration. In our experiments, it is found that different indicator locations did not have a significant effect on the actual attention allocation of the participants. As shown in Figs. 4 and 5, the pitching angle which was located in the good visual field did not earn more attention resource than the prediction of the theoretical model, and the heading, which was located in the poor visual field, did not lose attention resource compared to the prediction. This may because the distribution of the four indicators was not dispersed enough. This part of the study will be further performed in the next phase.

6. Conclusion

After making a comprehensive analysis of several influencing factors, such as the importance of information evaluated by the pilot, information detection efficiency and human error, a pilot attention allocation model was built from the perspective of fuzzy mathematics and cognitive psychology. According to the simulation experiments performed in our study, the model is suggested to be used for predicting the pilot's attention allocation to a group of indicators. Therefore, it can provide a reference for the human evaluation of cockpit interface design.

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